MEASUREMENT OF THE ELECTRON-DEUTERON INELASTIC SCATTERING CROSS SECTION AT MOMENTUM TRANSFER OF 0.5 FERMI^{-2}

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THESIS

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By

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ABSTRACT

Measurement of the inelastic electron-deuteron scattering cross section was made at a momentum transfer of 0.5 Fermi^{-2} ($q^2 = .5F^{-2}$) and for the scattering angles of 120°, 135°, and 150°. As a result the transverse and longitudinal parts of the cross section could be separated.

The spectrum cross sections measured also showed an indentation or "dip" which will require further study.

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I. INTRODUCTION

A. THE DEUTERON

The deuteron is the simplest of the nuclei being the only stable two nucleon system, i.e., composed of a proton and a neutron, while all other possible two nucleon systems (two protons and two neutrons) do not have any bound states.

A study of the static properties of the deuteron produces some interesting results. The magnetic moment of the deuteron is not the result of a vector addition of the magnetic moments of the proton and neutron. In addition, the existence of an electric quadrupole moment indicates that the deuteron has a preferred orientation in space. These properties indicate that the structure of the deuteron is not simple. This would lead one to believe that the strong interaction which binds the nucleons together is complicated. The study of the deuteron is further complicated by the fact that it has only one bound state, the ground state.

The ground state represents a weakly bound system with a binding energy of 2.226 MeV. This means that this is the minimum energy necessary to break the deuteron apart. When the deuteron breaks up, the nucleons are unbound and can make a transition into a continuum of states, this results in an energy continuum for the inelastic process instead of a sharp resonance.

It is this break up that provides an opportunity to study the structure of the deuteron and in turn the nature of the strong interaction.

B. THE VALUE OF ELECTRON-DEUTERON SCATTERING

Work has been done for many years in studying the photo-disintegration of the deuteron to measure the binding energy and to study the break up of the deuteron. The free photon has a disadvantage because only transverse photons exist for free electromagnetic fields and thus can only interact with the transverse part of the deuteron's electromagnetic field.

The electron has been used for many years as a tool in studying nuclear structure. They are useful because:

a) The electron is not a strongly interacting particle and therefore its interaction is electromagnetic. Quantum electrodynamics, even with all its problems, is well understood, while the strong interaction is not understood well at all.

b) The electron has a non-zero rest mass, therefore the virtual photons exchanged in the electromagnetic interaction do not have to satisfy the gauge condition and can therefore interact with the longitudinal part of the electromagnetic field.

In studying any scattering problem there is a parameter which is used to describe the interaction, the momentum transfer q. It is the difference between the initial and final four-momentum of the scattering particle and is a measure of the amount of momentum and energy delivered to the target. The zero rest mass photon has a fixed momentum transferred for a given interaction, while the electron can

interact delivering a variety of momentum transfers. This allows one to conduct several experiments under different conditions and have the momentum transfer identical.

The question arises whether the electron can be used to study the deuteron structure and particularly the break up of the deuteron into the proton and neutron. Electron-deuteron scattering has been done for many years for an incident energy from about 10 MeV to around 20 GeV [1,2]. The electron-deuteron scattering processes have several possible outcomes and they are:

a) $e + d \rightarrow e' + d'$

b) $e + d \rightarrow e' + n + p$

c) radiation of the electron

d) electron pion production.

Elastic scattering (a) from the deuteron has been done over the years to determine the electric form factor of the neutron [1,2] and the general structure of the deuteron.

In all scattering experiments one measures a cross section for the process being studied. One can then calculate, for elastic electron scattering, a cross section from quantum electrodynamics for a nucleus with no structure, this is called the Mott cross section. Since the nucleus does have structure the measured cross section for the scattering process and the Mott cross section will differ. The measure of the structure of the nucleus is the form factor (or structure factor) which is defined:

$$F^2(q^2) = \frac{\text{Experimental cross section}}{\text{Mott cross section}},$$

where q^2 is the momentum transfer squared.

If one again uses quantum electrodynamics and assumes a one photon exchange process with a target that has charge and magnetic structure the general form of F^2 is:

$$F^2(q^2) = A(q^2) + B(q^2) \tan^2(\theta/2).$$

Here q^2 is the same as before and θ is the scattering angle of the electron. In the case of electron-nucleon scattering the A and B are approximately the charge and magnetic form factor, respectively.

The radiation of scattered electrons (c) is also a result of electrodynamics. In the scattering process the electrons are accelerated and this causes any charged particle to radiate. This radiation causes the electron to loose energy and would thus change the measured cross section. Therefore, this effect must be corrected in the experimental data. This problem has been studied for a long time and the actual method used in these experiments is discussed in Section IV.

Pion production (d) does not occur for incident electron energies less than 150 MeV and was not considered for the experiments conducted at the linear accelerator facility (LINAC) at the Naval Postgraduate School.

The interaction of interest is the inelastic scattering in which the electron supplies the deuteron with enough energy to cause it to break apart.

C. THE INELASTIC ELECTRON-DEUTERON SCATTERING

The energy of the inelastically scattered electron is a function of the incident energy and the energy deposited in the deuteron system to cause it to break up. This break up does not occur until the deuteron is supplied with 2.226 MeV in the center of mass, but after this threshold is reached the deuteron will be able to absorb a continuum of energy and this produces a very broad inelastic spectrum. In our case we will be looking at electrons with an initial energy E scattered at an energy E' into a solid angle dΩ and an angle θ and measure the differential cross section

$$\frac{d^2\sigma(E,E',\theta)}{d\Omega dE'} \ .$$

If we use the same method as in elastic scattering we can define a form factor $D(E_x,q)$ in the same way (as a ratio of the experimental cross section to the Mott cross section). The additional parameter E_x represents the excitation energy of the deuteron when it breaks apart. Other authors use an equivalent parameter P which is the momentum of the proton in the deuteron center-of-mass.

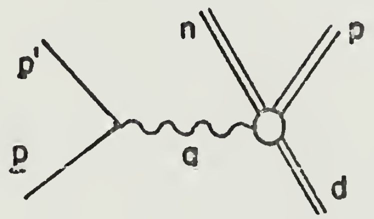
Jankus [3] derived a cross section for this process in the first Born approximation in which he assumed that the final states available to the nucleons were only the free nucleon states. This amounts to assuming that the electron interacts with only one of the nucleons and the other is only a spectator. This is called the impulse approximation.

In addition, he allowed the nucleons to have structure by including the nucleon form factors.

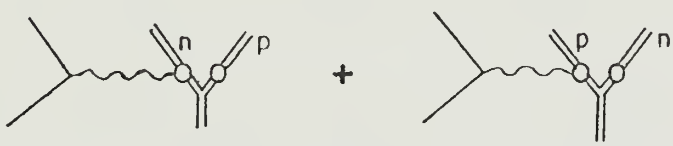
It is this study of the inelastic scattering that will give information about the structure of the deuteron.

II. THEORY

The simplest way to calculate the scattering cross section is to look at the Feynman diagrams for the process and determine the S matrix. In these diagrams time is represented as increasing upward. A single line represents an electron moving up or a positron moving down, while a waved line represents a photon and a double line represents a complex particle. For inelastic electron-deuteron scattering to second order (one photon exchange) the diagram would be:



If we use the impulse approximation this diagram can be represented as the sum of two interactions:



Now each diagram does appear to look the same and the S matrix for each term in the sum has the form:

$$S = \int d^4x' \; A^{e}_{\mu}(x') \; j^{\mu}_{\rho}(x') \; . \qquad (2\text{-}1)$$

For notations used see Reference [4].

Now if we assume that the initial and final states for the electron are plane waves we have:

$$A^e_\mu(x') = \frac{-i4\pi e}{q^2}\,\bar{u}(s',p')\ \gamma^e_\mu u(s,p)\ e^{iq\cdot x'} \tag{2-2}$$

while the nucleon contributions to each part of the S matrix is

$$j^\mu_\rho(x') + ie\psi_{f\rho}(x')(\gamma^\mu F_{1\rho}(q^2) + \frac{K_\rho}{2M_\rho} F_{2\rho}(q^2)\sigma^{\mu\nu}q_\nu)\psi_{i\rho}(x'). \tag{2-3}$$

Here ρ stands for proton or neutron, M is the nucleon mass, and $F_1(q^2)$ and $F_2(q^2)$ are the nucleon Dirac and Pauli form factors, respectively. The next problem is the choice of the initial and final state wave functions of the nucleons $\psi_i(x')$ and $\psi_f(x')$. The initial states of the nucleons are usually assumed to be described by the non-relativistic deuteron wave function in the Breit reference frame:

$$\psi_i(r_n - r_p) = N\begin{pmatrix}1\\ \pi_n\end{pmatrix}\begin{pmatrix}1\\ \pi_p\end{pmatrix}\psi_{NR}(r_n - r_p). \tag{2-4}$$

The π_i are two component operators defined by the relation:

$$\pi_i = 2\sigma_i\cdot p_i/(E_d+2M) \simeq \sigma_i\cdot p_i/2M,$$

$\psi_{NR}(r)$ is the usual non-relativistic deuteron wave function with u(r) as the S state component and w(r) as the D state component. The other difficulty is the choice of the final state wave functions. Jankus [3] chose plane wave final states for the nucleons, in other words he assumed that the nucleons were completely free particles after the deuteron broke up. By inserting this into (2-1) we get the S matrix. The cross section is obtained from the absolute square of the S matrix by including kinematic terms, integrating over all final momentum states not measured, summing over all

final spin states and dividing by the flux of the particle. Durand [5] shows that this gives:

$$\frac{d^2\sigma(E,E_x,\theta)}{d\Omega\ dE_x} = \sigma_{Mott} D(E_x,q) \tag{2-5}$$

where σ_{Mott}, the Mott cross section, is given by:

$$\sigma_{Mott} = \frac{\alpha^2 \cos^2(\theta/2)}{4E^2\sin^4(\theta/2)} \tag{2-6}$$

with α being the fine structure constant. The form factor $D(E_x,q)$ can be separated into longitudinal and transverse form factors which are related by D by:

$$D(E_x,q) = D_L(E_x,q) + (1+2\tan^2(\theta/2))\ D_T(E_x,q). \tag{2-7}$$

D_L and D_T are given by the relations:

$$D_L(E_x,q) = \eta M(P,q)(G_{ep}(q^2)+G_{en}(q^2))^2+N(P,q)(2+\eta G_{nm}(q^2)G_{pm}(q^2)) \tag{2-8}$$

and

$$D_T(E_x,q) = \eta[M(P,q)(G^2_{mp}(q^2)+G^2_{mn}(q^2))+1/3\ N(P,q)G_{mp}(q^2)G_{mn}(q^2)] \tag{2-9}$$

$\eta = q^2/4M^2$ and the alternate physical nucleon form factors are:

$$G_e\ (q^2) = F_1\ (q^2) + \eta\kappa\ F_2\ (q^2) \tag{2-10}$$

$$G_m\ (q^2) = F_1\ (q^2) + \kappa\ F_2\ (q^2).$$

The other components of the form factors are:

$$M(P,q) = \tfrac{1}{2}\int_0^{\pi} F^2(\theta)\ d(\cos\theta) \tag{2-11}$$

and

$$N(P,q) = \tfrac{1}{2} \int_0^{\pi} F(\theta)\, F(\pi-\theta)\, d(\cos\theta) \tag{2-12}$$

with

$$F(\theta) = \int_0^{\infty} j_0[(\tfrac{1}{2}q^2 + P^2 - Pq\cos\theta)\, r]\, u(r)\, dr.$$

u(r) is the S state component of the deuteron wave function, $j_0(x)$ is the first half order spherical Bessel function; P, the momentum of the proton in the deuterons center-of-mass, is defined by $P^2 \simeq ME_x$.

Thus the form factor of the inelastic process depends on the wave function of the ground state of the deuteron. Therefore, any deuteron model which is to be accepted as describing the real deuteron must account for the measured inelastic electron-deuteron scattering spectrum.

III. EXPERIMENTAL PROCEDURES

The electrom beam used in this experiment was produced by the linear accelerator facility (LINAC) of the Naval Postgraduate School. It is a low intensity accelerator (a maximum average current of about 20 μamp) and has a maximum energy of about 100 MeV. A detailed description of the accelerator and its general operation have been given in Ref. 1 and 6.

The electron beam was focused on a 3 inch diameter cylinder which contained the deuteron target in the form of deuterium gas. The gas was at a pressure of about 10 atmospheres and with the use of a liquid nitrogen reservoir attached to the target cylinder was kept at a temperature of about 77°K. The temperature was monitered by the use a copper resistance thermometer and it was found that during the experiment the temperature did not change more than .25°K. The details of the gas target and the thermometer are discussed in Ref. 7.

The scattered electrons were momentum analyzed by a 16" double focusing magnetic spectrometer and detected by a ten channel scintillation counting system which is described in Ref. 1.

The incident beam was measured by the use of a secondary emission monitor (SEM) which was calibrated against a Faraday Cup. The output of the SEM was integrated using a Cary Vibrating Reed Electrometer and a .1, 1, or 10 μf capacitor.

The background was measured with the target filled with deuterium and the spectrometer set at an energy about 1 MeV above the incident energy.

The elastic spectrum, which was used for the radiative tail subtraction and cross section normalization, was measured by making five settings of the spectrometer in steps of one fifth the average channel resolution in such a way that the elastic peak was in channels 5 through 7. The spectrometer was then adjusted to include the inelastic spectrum (about 2.2 MeV below the elastic peak). A second setting was then made with the spectrometer stepped down by a value equal to one half the channel resolution. Finally in steps of 2 to 5 MeV data were gathered for energies down to 20 MeV below the elastic peak. For each setting, the number of electrons counted in each channel (counts), the spectrometer setting, the time the setting took, the integration of the SEM output in volts and the capacitance of the integrator were recorded.

IV. DATA REDUCTION

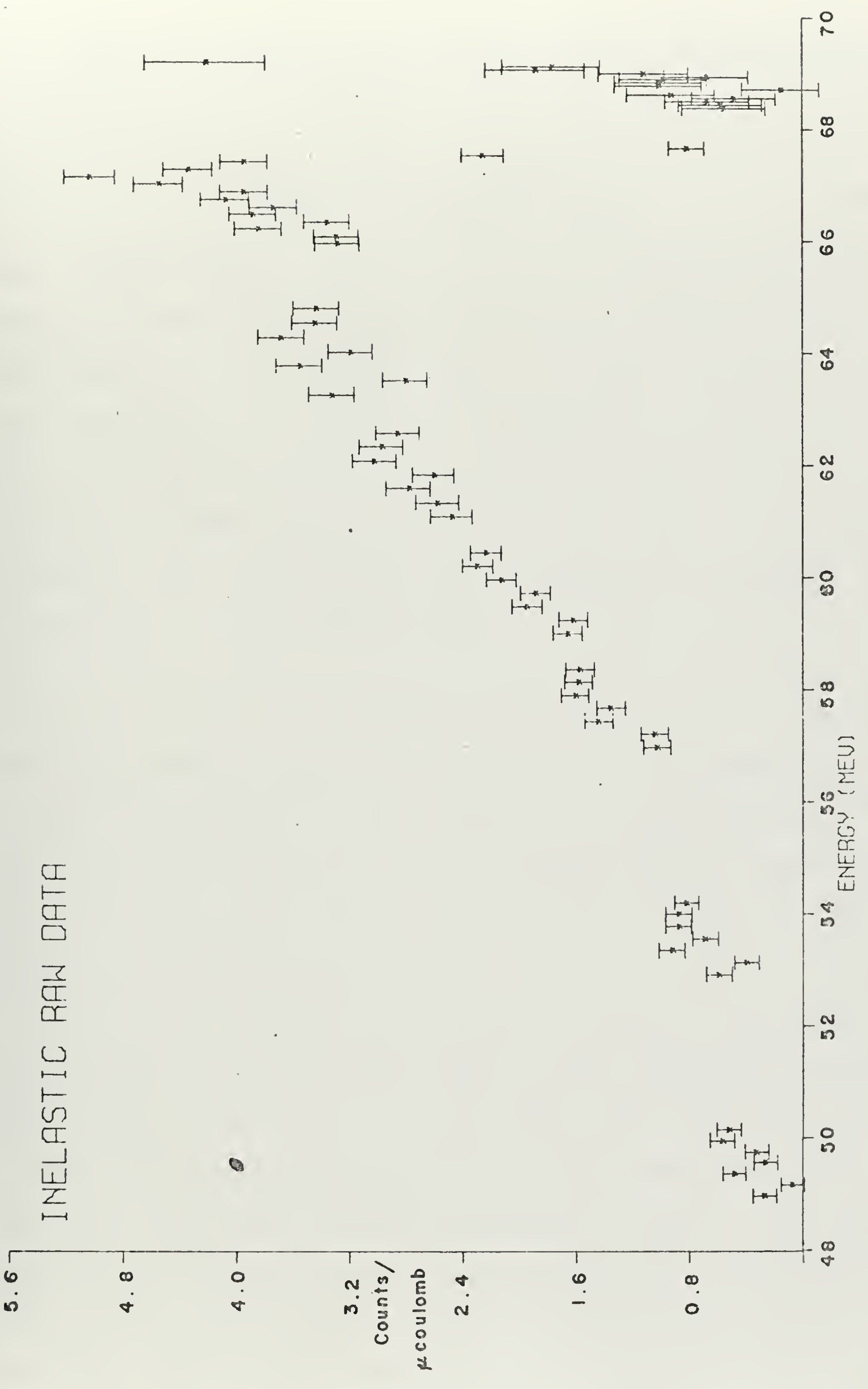
The raw counting data acquired from the 10 channel counting system was in the form of counts in each of the channels for a spectrometer setting and an integration (in volts and the capacitance) of the SEM output current. The energy of the electrons in each channel was determined by the method described in Ref. 1. Then the data in each channel was corrected for counting rate losses and the background was subtracted. Finally the counts were corrected for the relative efficiencies of each channel [Ref. 1] and normalized to one microcoulomb of integrated current from the SEM. The energy and corrected and normalized counts for all channels and spectrometer settings form the "raw" data spectrum. Such a spectrum is shown in Figures 1 and 2. Figure 2 shows a close up of the inelastic spectrum without the presence of the elastic peak.

The inelastic spectrum was enhanced by the presence of the radiative tail from the elastic peak (see Figures 1 and 2). The effect of the tail was subtracted for the inelastic spectrum by fitting the data from the elastic tail above the inelastic threshold to a polynomial (in the least squares sense) of the form:

$$a_0 + a_1 x + a_2 x^2 ,$$

where $x = (E_p - E)^{-1}$ and E_p is the energy of the elastic peak. The polynomial was used as the function for the tail in the subtraction from the inelastic spectrum.


RAW DATA
Counts/μcoulomb
35
30
25
20
15
10
5
48
50
52
54
56
58
60
62
64
66
68
70
ENERGY (MEV)
fig. 1



INELASTIC RAW DATA
Counts/ μcoulomb
5.6
4.8
4.0
3.2
2.4
1.6
0.8
ENERGY (MEV)
48
50
52
54
56
58
60
62
64
66
68
70

fig.2

The cross section was obtained from the counting spectrum by:

$$\frac{d^2\sigma(\theta,E')}{d\Omega dE'} = \frac{N_s(E')}{N_i \; Res(E')\Delta\Omega \; nt} \qquad (4\text{-}1)$$

where $N_s(E')$ is the number of electrons (counts) scattered into the counter measuring electrons of energy E', N_i is the number of incident electrons, $\Delta\Omega$ is the solid angle of the spectrometer with respect to the target (in our case this is 1.83×10^{-3} steradians), n is the density of the deuterons in the target in units of cm^{-3}, and t is the effective target thickness in cm. The number of incident electron N_i was calculated by:

$$N_i = \frac{10^{-3}}{e\varepsilon} ,$$

where e is the charge on the electron (in coulombs) and ε is the efficiency of the SEM (which is 6.1% in our case). The density of the target was calculated from the pressure and temperature of the gas. The details of these calculations are given in Reference 6.

The cross section of the elastic peak was calculated in a similar way except the spectrum was integrated to give the elastic cross section: $d\sigma(E,\theta)/d\Omega$. The radiation of scattered electrons cause them to be lost from the peak and thus makes the elastic cross section smaller. For the integrated peak Tsai [8] has shown this effect can be corrected by a multiplicative factor and this correction was applied to the elastic cross section. This produces a cross

section for elastic scattering that has been corrected for all effects except the uncertainty in some of the experimental parameters (such as target thickness and SEM efficiency).

The measured elastic deuteron form factor G^2 is calculated by dividing the measured cross section by the Mott cross section. Then by using the magnetic corrections [1] a measured value for the deuteron electric form factor G^2_{ed} was calculated. If we assume now that the correct form of G^2_{ed} is $G^2_{ed}(q^2) = 4G^{S\,2}_e(q^2)\ F_d(q^2)$, where $G^{S\,2}_e$ is the nucleon scalar form factor and F_d is the elastic deuteron structure factor (calculated from the Feshbach-Lomon wave function), we can then determine the necessary factor to account for all the uncertainties in the experiment which would make the experimental form factor correspond to the theoretical form factor. This normalizing factor is then applied to the inelastic spectrum to give a corrected measured value. The inelastic spectrum is then said to be normalized against the elastic peak. This is done because all uncertainties effect both cross sections in the same way.

The finite energy resolution of the incident electrons affects the shape of the spectrum, therefore the data were next corrected for this resolution. The elastic peak was used to approximate the energy distribution of the incident electrons. Since the effect of the resolution is small the first approximation is that the measured spectrum is the correct spectrum for monoenergetic incident electrons of an

energy in the center of the distribution. The spectrum was adjusted by moving the electrons on the edges of the distribution into the peak and shifting the corresponding portion of the inelastic spectrum to produce a more correct spectrum. This process was iterated until all the electrons in the distribution had been shifted to the center and the inelastic spectrum adjusted correspondingly. This process produces a spectrum which represents the inelastic scattering from a monoenergetic electron source.

Finally the data must be corrected for the effects of radiation. When the electrons lost energy in the radiative process they are detected in another part of the spectrum, thus the shape of the spectrum is changed. Therefore, the same method as used for the elastic peak cannot be used here. The actual method used in correcting the inelastic spectrum is outlined by Crannell [9] and it was used with the work of Tsai [10].

Once the spectrum was corrected for the effect of the resolution of the incident electrons and the radiation it was divided by the Mott cross section and produced $D(E_x,q)$. An example of the final spectrum $D(E_x,q)$ is shown in Figure 3.

Such data spectra were taken for three different angles (120°, 135°, and 150°) at the same values of $q(q^2=.5)$ and E_x (this was accomplished by hand fitting the spectrum on a graph and reading off the graph). These data were ploted vers $(1 + 2\tan^2(\theta/2))$. As one can see form (2-7) these points

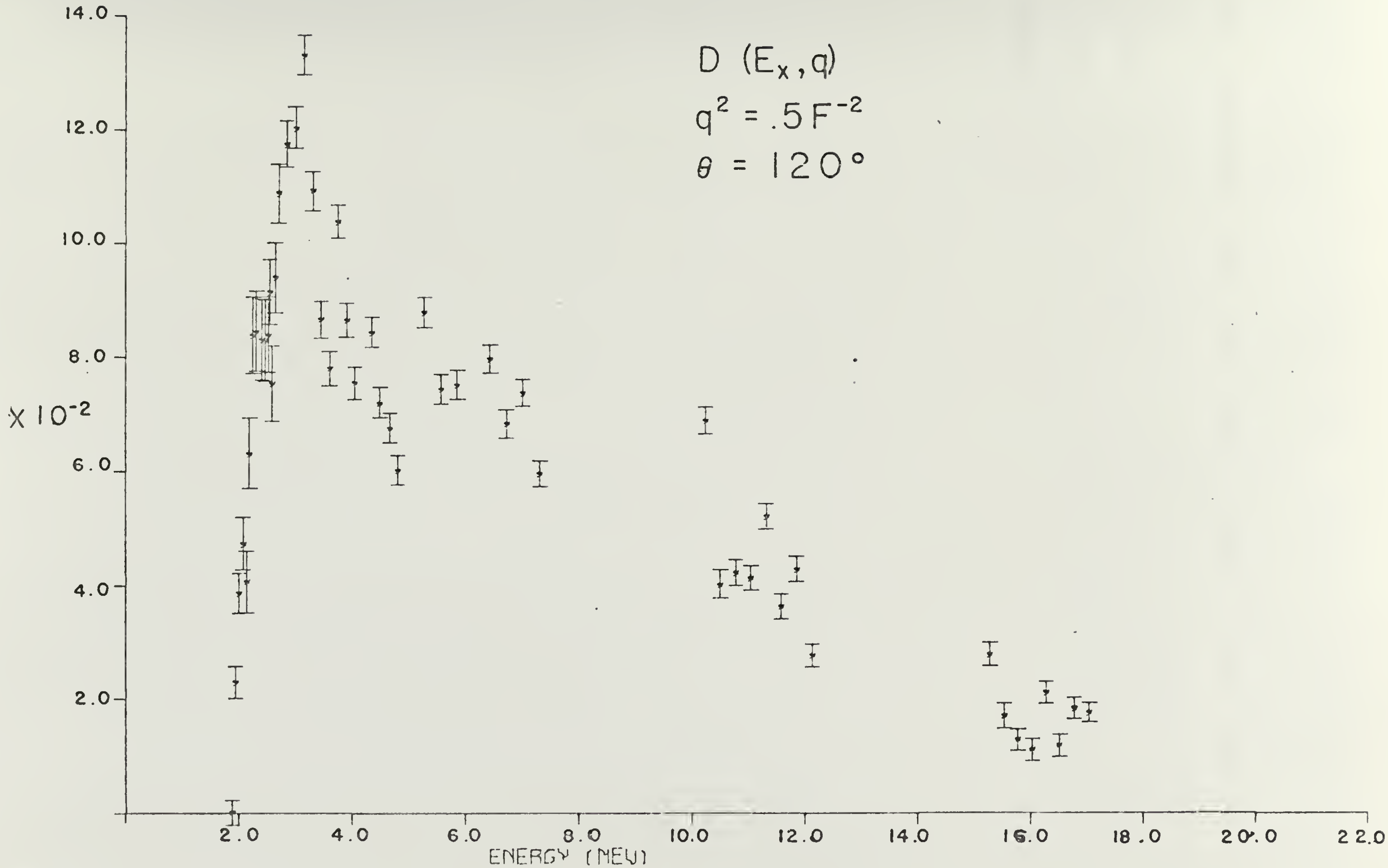

D (E_x,q)
q^2 = .5F^-2
θ = 120°
X 10^-2
ENERGY (MEV)
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
18.0
20.0
22.0

fig.3

should lie on a straight line. Figure 4 represents one of our best plots and Figure 5 shows one of the worst. These are Rosenbluth plots and the intercept of the straight line fit yields the longitudinal form factor $D_L(E_x,q)$, while the slope gives the transverse form factor $D_T(E_x,q)$. The results of these fits are presented in Table I and shown in Figures 6 and 7.

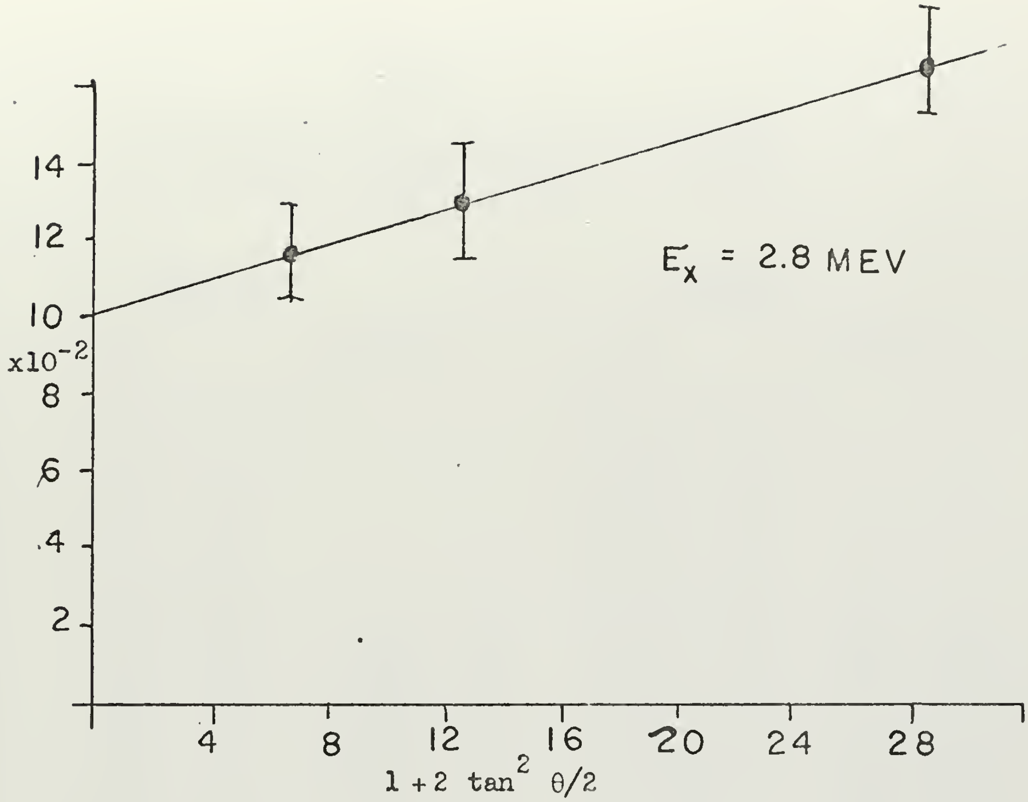

14
12
10
x10-2
8
6
4
2
4
8
12
16
20
24
28
1 + 2 tan2 θ/2
Ex = 2.8 MEV

Fig. 4.

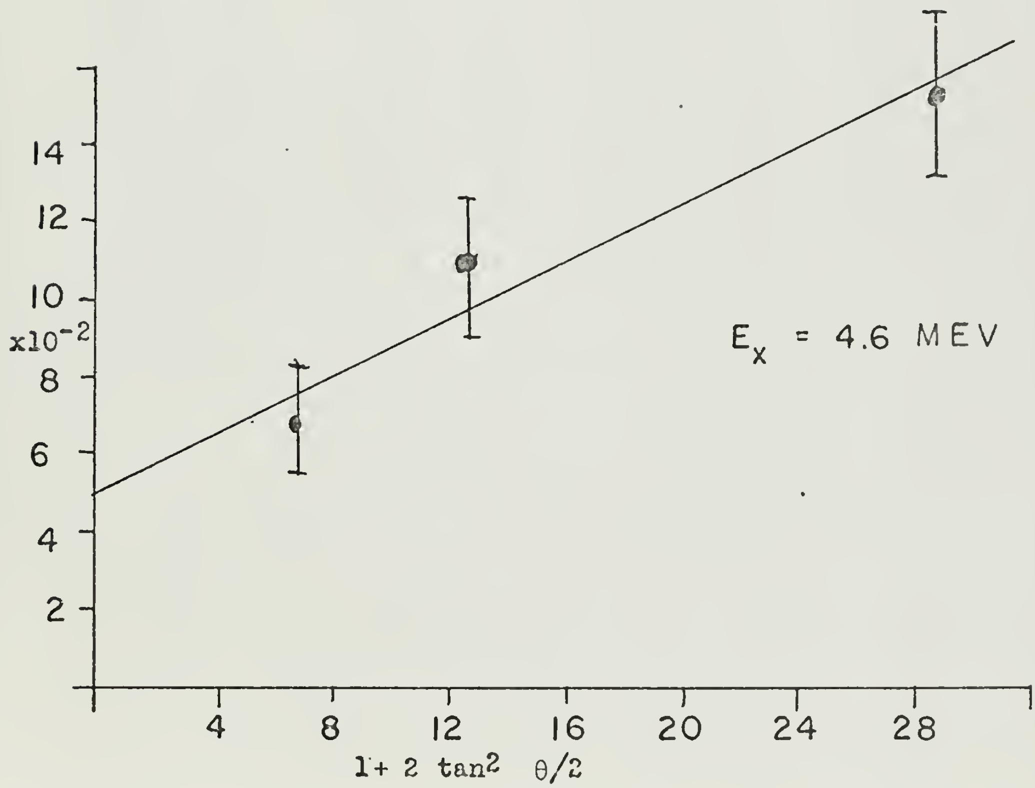
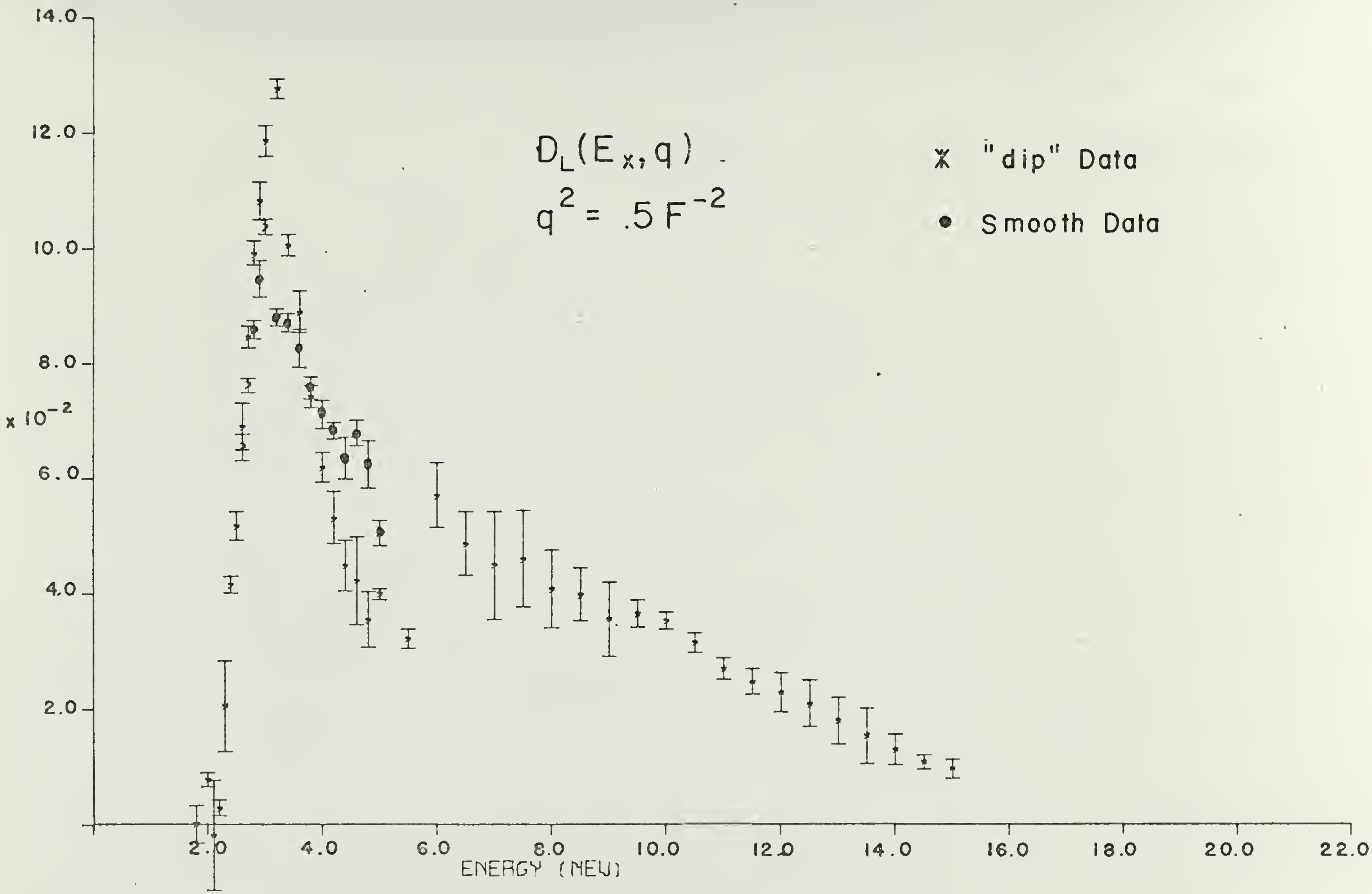

14
12
10
x10-2
8
6
4
2
4
8
12
16
20
24
28
1+ 2 tan2 θ/2
Ex = 4.6 MEV

Fig. 5.

TABLE I

Transverse and Longitudinal Form Factors
For Inelastic Electron-Deuteron Scattering
at $q^2 = .5\ F^{-2}$

E_x MEV	$D_L(E_x,q) \times 10^{-2}$ "dip"	smooth	$D_T(E_x,q) \times 10^{-3}$ "dip"	smooth
1.8	0.00 ± .34		0.0 ± .20	
2.0	0.77 ± .14		4.57 ± .10	
2.1	-0.20 ± .97		6.68 ± .65	
2.2	0.28 ± .15		7.87 ± .11	
2.3	2.06 ±.80		7.63 ± .58	
2.4	4.17 ± .16		6.54 ± .11	
2.5	5.18 ± .26		5.55 ± .19	
2.6	6.90 ± .41	6.54 ± .24	4.28 ± .30	4.76 ± .16
2.7	8.45 ± .20	7.62 ± .15	2.93 ± .18	4.35 ± .21
2.8	9.90 ±.17	8.50 ± .21	2.29 ± .14	3.84 ± .18
2.9	10.87 ± .34	9.47 ± .34	2.06 ± .22	3.84 ± .23
3.0	11.86 ± .28	10.37 ± .15	1.44 ± .24	2.97 ± .19
3.2	12.76 ± .18	8.80 ± .15	0.97 ±.43	3.20 ± .21
3.4	10.05 ± .18	8.71 ± .16	1.37 ± .11	3.20 ± .11
3.6	8.89 ± .37	8.25 ± .24	1.46 ± .24	3.39 ± .23
3.8	7.42 ± .20	7.56 ± .20	2.20 ± .14	3.20 ± .14
4.0	6.19 ± .27	7.11 ± .24	2.75 ± .17	3.52 ± .16
4.2	5.31 ± .46	6.82 ± .37	3.20 ± .29	3.47 ± .17
4.4	4.48 ± .46	6.35 ± .37	3.79 ± .30	3.48 ± .24
4.6	4.22 ± .78	6.79 ± .56	3.89 ± .52	2.93 ± .34
4.8	3.55 ± .48	6.24 ± .41	4.58 ± .32	3.43 ± .27
5.0	3.99 ± .11	5.05 ± .11	4.35 ± .15	3.98 ± .21
5.5	3.22 ± .19		4.35 ± .13	
6.0	5.71 ± .56		3.02 ± .37	



14.0
12.0
10.0
8.0
x 10^{-2}
6.0
4.0
2.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
18.0
20.0
22.0
ENERGY (MEV)
$D_L(E_x, q)$
$q^2 = .5\,F^{-2}$
"dip" Data
Smooth Data

fig. 6

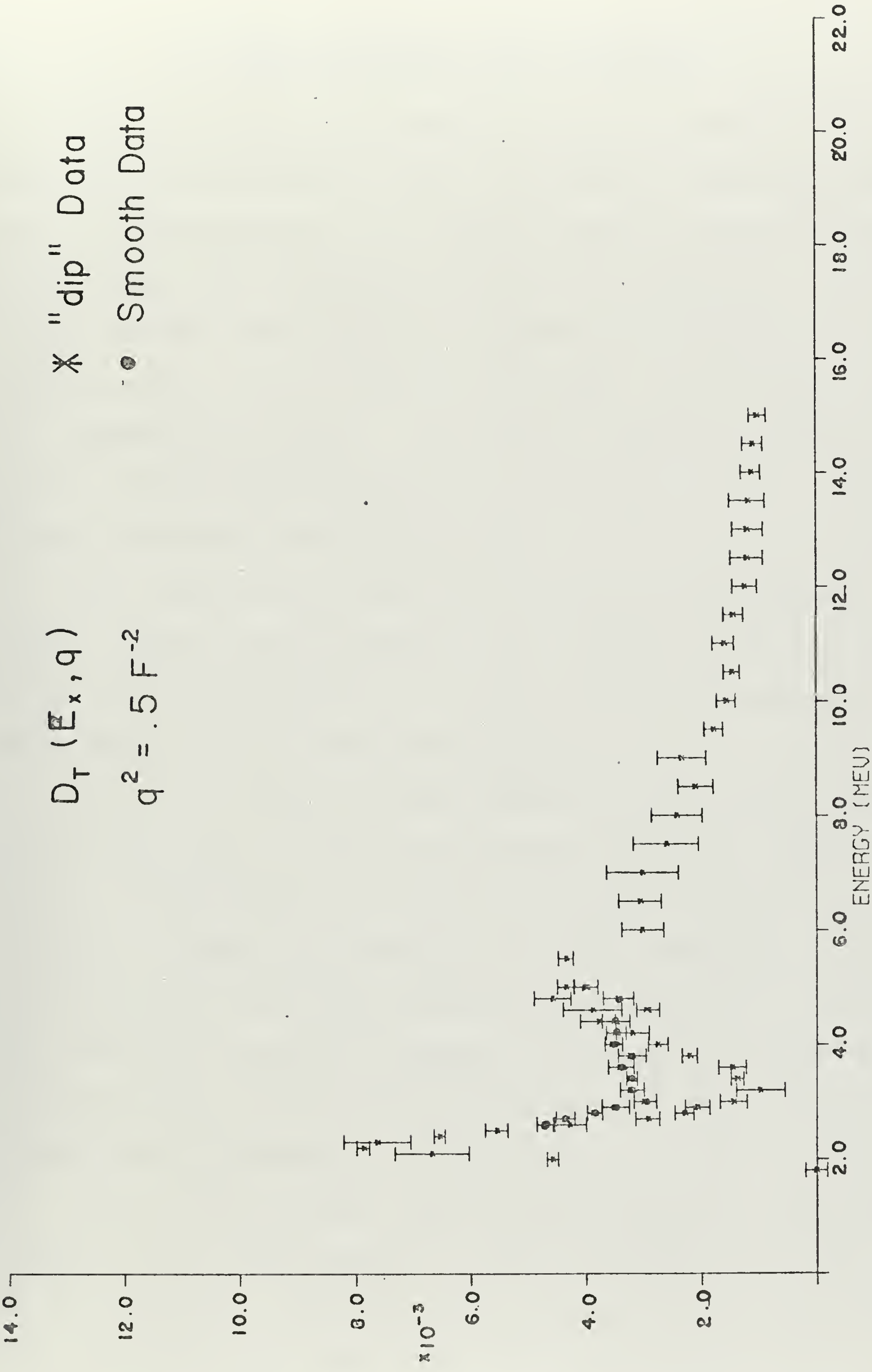

$D_T\,(E_x, q)$
$q^2 = .5\ F^{-2}$
"dip" Data
Smooth Data
$\times 10^{-3}$
ENERGY (MEV)
14.0
12.0
10.0
8.0
6.0
4.0
2.0
2.0
4.0
6.0
8.0
10.0
12.0
14.0
16.0
18.0
20.0
22.0

fig. 7

V. ERROR DISCUSSION AND CONCLUSION

The errors are both statistical and systematic. The most obvious systematic errors are those in the uncertainty in the determination of the target density, target thickness, solid angle, and the number of incident electrons. However, since the data were normalized against the deuteron elastic peak, the only error would come from the choice of the elastic deuteron form factor. Reference 1 indicates that the choice of the Feshbach-Lemon wave function is good. Therefore, this error should be minimal.

The statistical errors are inherent in the process being studied (the distribution was Poisson), and this was minimized by accumulating as large a number of counts in each channel as the time would allow.

The most serious possible source of error was in the tail subtraction. Incorrect shifting of the tail function in the subtraction process could change the shape of the spectrum. Also, it is possible that the polynomial of the type used does not really represent the elastic tail under the inelastic spectrum. However, at present, it seems that these are not serious sources of error, but they should be studied more carefully.

Now it will be noted that in the form factor spectrum (Figure 3, see also Figure 2) there is an apparent "dip" in the spectrum. There does not appear to be any experimental reason for this "dip" that is evident at this time. In

addition the Rosenbluth plots do not show a preference for the "dip" data or for a smooth spectrum. Therefore, the fits for D_L and D_T using both the "dip" spectrum and the smooth spectrum are presented. The data in Table I and in Figure 6 and 7 show the smooth spectrum data only when it is different from the "dip" data.

This "dip" will require additional study. This can be done by making more careful measurements in this region and by carefully studying the effects of the tail subtraction. If the "dip" is a real effect then it is obvious that any deuteron must show this effect in the predicted inelastic electron-deuteron scattering cross section.

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13. ABSTRACT

Measurement of the inelastic electron-deuteron scattering cross section was made at a momentum transfer of 0.5 Fermi^{-2} ($q^2 = .5F^{-2}$) and for the scattering angles of 120°, 135°, and 150°. As a result the transverse and longitudinal parts of the cross section could be separated.

The spectrum cross sections measured also showed an indentation or "dip" which will require further study.

KEY WORDS	LINK A		LINK B		LINK C	
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